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UNITED STATES DEPARTMENT OF AGRICULTURE

BULLETIN No. 532

Contribution from the Office of Public Roads and Rural Engineering
LOGAN WALLER PAGE, Director

Washington, D. C. PROFESSIONAL PAPER October 13, 1917

THE EXPANSION AND CONTRACTION OF CONCRETE AND CONCRETE ROADS

By

A. T. GOLDBECK, Engineer of Tests, and F. H. JACKSON, JR.
Assistant Testing Engineer

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Observation of concrete roads shows that most of the irregularities of wear make their initial appearance at expansion joints and at transverse and longitudinal cracks. Soon after a crack is formed traffic begins to batter down the edges, and unless immediate and effective maintenance measures are adopted, each succeeding vehicle will act with greater destructive effect. Under such conditions and without proper maintenance, little time elapses before depressions are formed in the road surface, which lessen the life of the road and render it decidedly unpleasant to the fast-moving traffic generally carried by concrete roads. Improperly maintained expansion joints wear in a manner similar to cracks, and the cost of their maintenance is dependent upon their frequence.

Cracks result when the tensile strength of the concrete has been exceeded, or compression cracks may be caused in rare instances by excessive expansion without proper provision for such a movement. Tension may occur in a concrete pavement as the result of settlement or upheaval, in which case the pavement is stressed as a slab, and, if overstressed, will crack on the tension side. Most transverse cracks, however, are caused by contraction due to two principal phenomena: 1, decrease in temperature; 2, drying out of water from the concrete.

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An extended series of laboratory and field tests was begun in 1910 by the Office of Public Roads to make a close study of expansion and contraction movements of concrete pavements. These included detailed attention to the spacing, design, and movement of expansion joints. It is the purpose of this bulletin to present the results of these experiments in the hope that they will be of some value to those interested in work of this nature. No attempt will be made herein to apply the results obtained to the practical side of road construction, although certain broad conclusions will be drawn from the results which will be available for immediate application by the engineer.

LABORATORY MEASUREMENTS OF EXPANSION AND CONTRACTION.

It has been established by other investigators[1] that concrete expands on being heated and contracts on cooling by an amount differing very little from that of steel. A coefficient of 0.0000055 per degree Fahrenheit seems to express accurately the effect of temperature. Therefore, with change in temperature of 100° F., a 100-foot length of concrete road, if unrestrained by friction at the base, would expand or contract $0.0000055 \times 100° \times 100$ feet $= +0.055$ feet or 0.66 inch. This phenomenon alone, without considering any other influences, probably accounts in many instances for the cracking of concrete pavements.

In view of the probable reliability of the already established temperature coefficient of expansion, all efforts of the laboratory were directed toward obtaining the change in length of concrete due to other causes. It has been shown, originally by Bauschinger and subsequently by other investigators, that both neat cement and mortar contract to a considerable degree upon hardening in air, while, on the other hand, they show considerable expansion when placed in water. Some of the values of contraction of neat cements and mortars, reported by White in the 1911 Proceedings of The American Society for Testing Materials, are as follows:

Shrinkage of neat cement kept in air.

	Per cent.
7 days (average of 6 specimens)	0.109
28 days (average of 6 specimens)	.190
6 months (average of 6 specimens)	.236
1 year (average of 5 specimens)	.270
2 years (average of 5 specimens)	.289
4 years (average of 5 specimens)	.322

[1] Kellar, "Volumänderungen von Cementen verschiedener Mischung bei wechseldner Temperatur and wechseldner Feuchtigheitsgrad," Tonind. Zeit. 19, 469 and 487, 1894.
Pence, W. D., "The Coefficient of Expansion of Concrete," Eng. News, 46,380 (1901).
Norton, Chas. I., "Some Thermal Properties of Concrete," J. Am. Soc. Mech. Eng., June, 1913, p. 1012.
Rudeloff and Sieglerschmidt, "Untersuchungen über die Langenänderungen von Betonprismen beim Erharteñ und in folge Temperaturwechsel," Deutsch. Auschuss für Eisenbeton, Heft 23, 1913.

According to these figures, neat cement shrinks about $2\frac{1}{8}$ inches in 100 feet when kept in air six months, and in four years the shrinkage, due merely to the drying out of the moisture, amounts to almost 4 inches in 100 feet. Mortar mixed in the proportions of 1 part of cement to 3 parts of sand, when allowed to harden in the air, shrinks, according to White's results, from 0.08 per cent to 0.1 per cent. These figures confirm in a general way the previously published figures of Bauschinger and others.

As neat cement and mortar were known to have this physical characteristic of expanding and contracting, depending upon their moisture content, it was considered reasonable to suppose that concrete, too, would show the same general behavior. The following laboratory tests were made on concrete to determine the amount of movements produced by the drying out and absorption of water. These movements, combined with temperature movements, probably account for most of the expansion and contraction of concrete pavements, and a knowledge of their values is of assistance in the design of expansion joints.

DESCRIPTION OF EXPANSION AND CONTRACTION SPECIMENS.

White and the earlier investigators made tests on the change in length of neat cement and mortar with specially designed micrometers on very small specimens, White's being only 4 inches in length. Obviously it would be impossible to use such small test pieces as these to determine the expansion and contraction of concrete containing coarse aggregates, and the type adopted was a column 8 inches square and 5 feet high. The column form of specimen was used to permit the free expansion of one end, in this way preventing friction from affecting the accuracy of the measurements.

PREPARATION OF SPECIMENS.

All concrete mixtures were proportioned by weight with a standard brand of Portland cement, Potomac River sand, and crushed gneiss or gravel. The cement was normal and passed the specifications of the American Society for Testing Materials. The sand was coarse and clean and considered a good grade of concrete sand. All concrete was hand mixed and was made of various consistencies. The specimens of very dry consistency required hard tamping to consolidate the concrete in the mold, while those of wet consistency were made simply by puddling the mixture in place. The amount of water used for the dry mixtures was about 8.5 per cent of the weight of dry materials. For the wet mixtures from 10 to 12 per cent was used.

MEASURING APPARATUS.

Referring to figure 1, it will be noted that to measure the change in length of the specimen, crossbars of steel one-half inch square were cast in the concrete. They were placed 50 inches apart, center to center, and this was considered the gauge length of the measurements. On each end of these bars a plug of steel with a rounded conical point was fastened, and micrometer measurements were taken between these points on each side of the specimen. Two readings were taken, so that unequal movements of the two sides of the specimen could be cared for by averaging the readings, thus obtaining expansion or contraction along the center line.

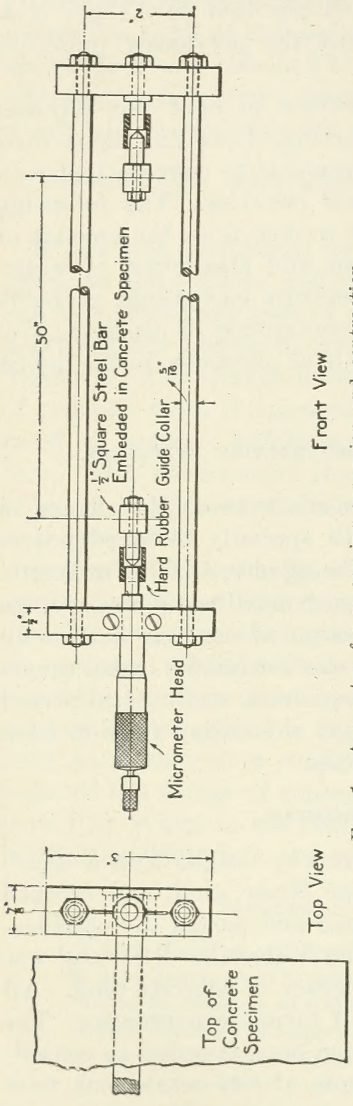


FIG. 1.—Apparatus for measuring expansion and contraction.

For obtaining the readings a special form of instrument (fig. 1) was designed and constructed in the laboratory. It consisted of a micrometer head reading to 0.0001 inch mounted at the end of a steel yoke. This yoke contained two steel rods five-sixteenths of an inch in diameter bolted to two end crosspieces, one holding the micrometer and the other a flat-ended steel pin. In taking measurements the flat-ended pin was held in contact with the lower conical point of the specimen, and the micrometer was screwed down to contact with the upper conical point. During the initial readings electrical contact was used in order to read the micrometer to the nearest 0.0001 inch. This, however, was discarded when it was found that readings of sufficient accuracy could be attained without it. In order that any change in the measuring instrument, due to wear or accident, might be detected, readings were taken repeatedly on a steel gauge bar hung from the specimen. Before any reading was made the instrument was hung alongside the specimen for a sufficient time to

bring it to constant temperature as determined by a thermometer likewise hung beside the specimen. A thermometer was inserted also in a horizontal orifice in the middle of the concrete specimen, and the temperature was noted at each reading. Finally, all readings were corrected to eliminate the effect of differences in temperature, whether due to chemical activity of the cement in hardening or to external changes. In figure 2 is shown a specimen with measuring instrument attached.

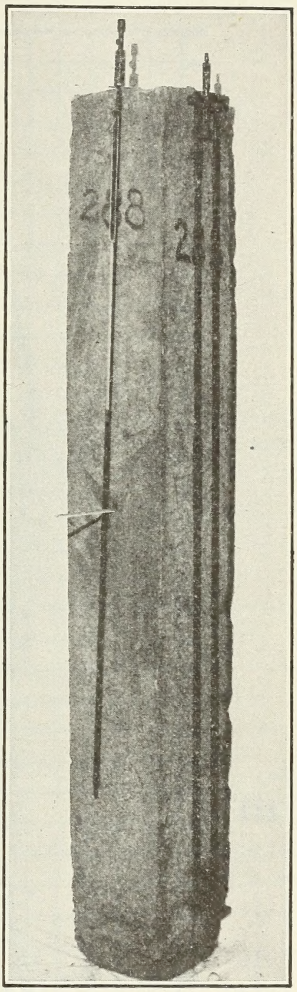


FIG. 2.—Specimen and apparatus for measuring the expansion and contraction of concrete.

RESULTS OF EXPANSION AND CONTRACTION MEASUREMENTS.

The results of these laboratory measurements are best seen by reference to the following curves:

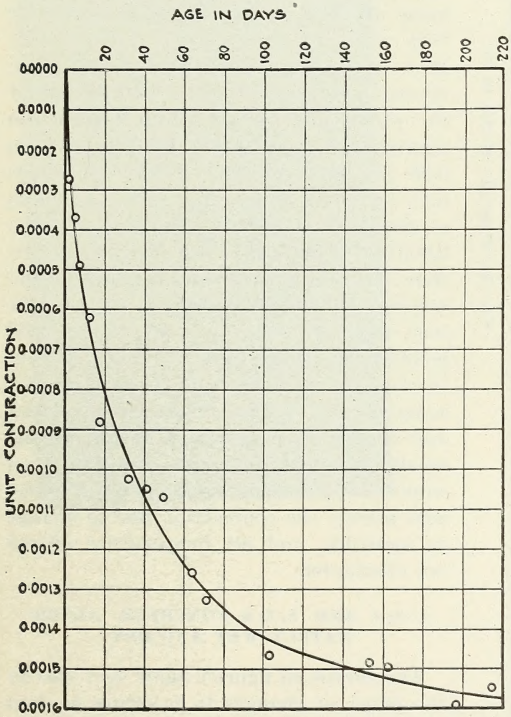


FIG. 3.—Neat cement, stored in air.

NEAT CEMENT, STORED IN AIR.

On figure 3 is shown a typical shrinkage curve of neat cement stored in the warm, dry air of the laboratory. It will be seen that shrinkage takes place immediately, and at the age of 6 months a total shrinkage of 0.155 per cent, or $1\frac{7}{8}$ inches, in 100 feet took place. This is much less than the results of White, who observed a shrinkage of 0.236 per cent, or $2\frac{7}{8}$ inches, in 100 feet.

1:2 AND 1:3 MORTAR, STORED IN AIR AND ALSO IN WATER.

The shrinkage of mortar when stored in air and the expansion when stored in water are shown clearly on the diagrams in figure 4. Note that the changes are somewhat greater in the 1:2 than in the 1:3 mortar. The shrinkage of air-cured 1:3 mortar which has been allowed to dry out is approximately 0.078 per cent at the age of 6 months, and that of 1:2 mortar at the same period is 0.085 per cent, which figures are quite like those of other investigators. It will be noted that both the 1:2 and 1:3 mortars have expanded when immersed in water, and at 6 months the values for the respective mortars are 0.015 per cent for 1:3 and 0.025 per cent for 1:2.

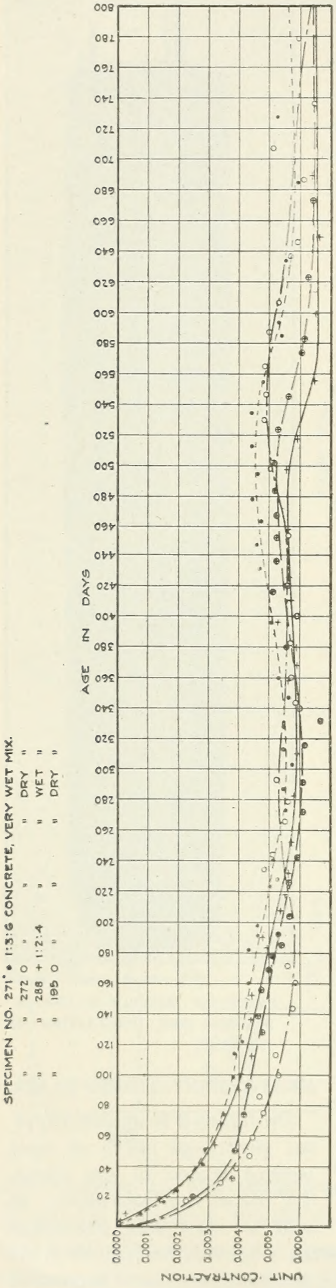


FIG. 5.—Concrete stored in air.

CONCRETE STORED IN AIR.

On figure 5 is shown the behavior of concrete when it is allowed to dry out immediately after molding. The specimens are 1:2:4 and 1:3:6 mixtures of very wet and of very dry consistencies. It is seen that contraction takes place almost immediately, due to drying out of the water, and at the age of 1 week the approximate contraction is from 0.01 to 0.03 per cent, or from 0.0001 to 0.0003 inch per inch of length. If the modulus of elasticity of concrete is assumed to be 2,000,000 pounds per square inch in tension, the tensile stress that would be developed by a contraction of only 0.0001 inch per inch of length would be 200[1] pounds per square inch. Unless free contraction of the concrete were provided some of this stress would be developed and cracking surely would result, as the tensile strength of the concrete then would be exceeded. These curves represent merely the contraction due to change in moisture, and all temperature effects are eliminated.

1:2:4 AND 1:3:6 CONCRETE, ALTERNATELY WET AND DRY.

The curves on figure 6 show very clearly the effect of changes in moisture content on the change in length of concrete. The specimens were mixed in different proportions and consistencies, and all were kept wet for 15 days after pouring the

[1] The "flow" effect of concrete probably will decrease this figure. This is mentioned later.

UNIT CONTRACTION EXPANSION

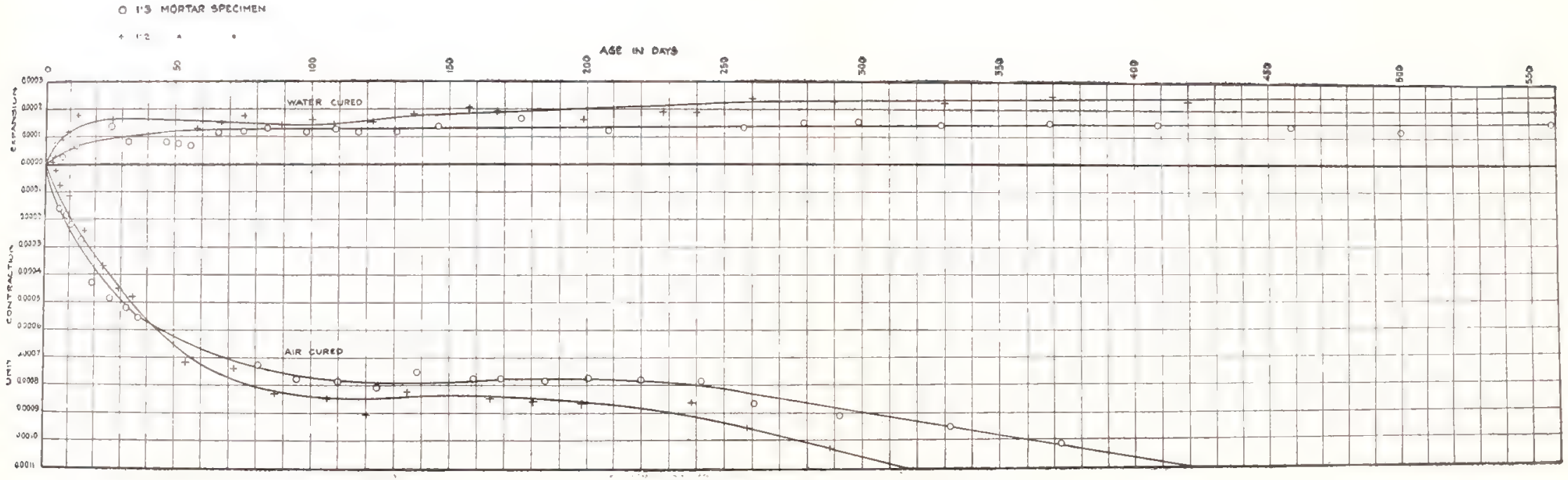


FIG. 4.—1 : 2 and 1 : 3 mortar, stored in air and also in water.

UNIT CONTRACTION EXPANSION

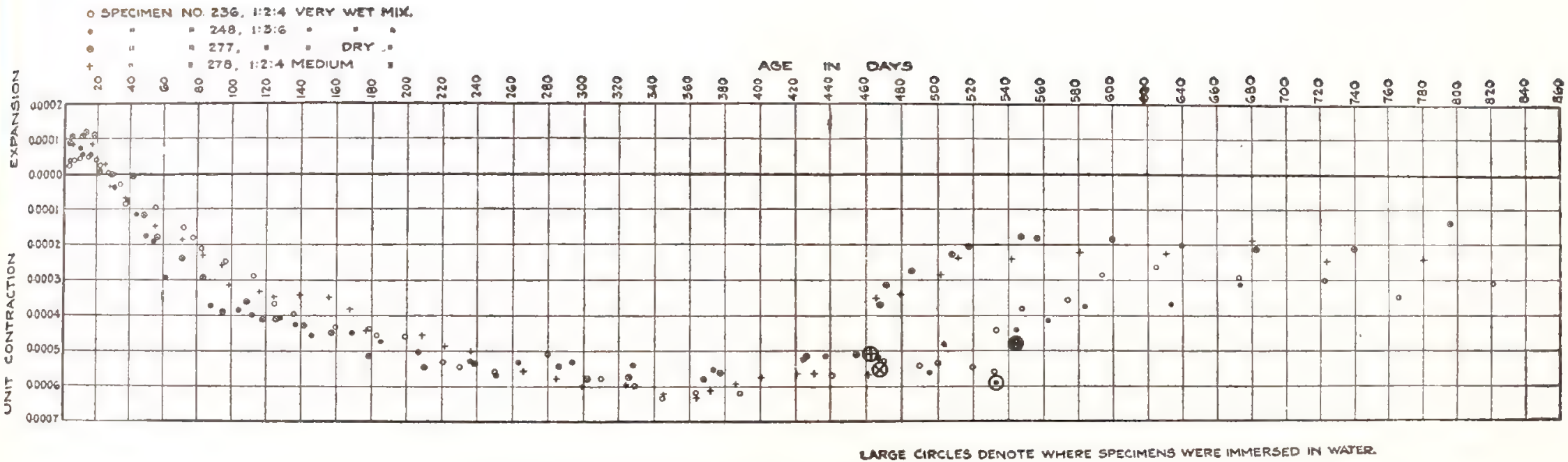


FIG. 6.—Expansion and contraction of 1:2:4 and 1:3:6 concrete alternately wet and dry.

concrete. This was done by covering them with burlap and keeping the burlap wet constantly. As soon as the concrete had become sufficiently hard, or in most instances not over two days after pouring, the forms were removed and initial readings of the specimens were made.

Referring to the curves, which are plotted with age in days as abscissas and with unit expansions and contractions as ordinates, note that during the first 15 days when the specimens were kept wet there was a continuous expansion, the maximum amounting to about 0.0001 inch, or 0.01 per cent. At the end of 15 days the specimens were permitted to begin drying out, and the effect of this drying is seen on the curve, which drops, or shows contraction, immediately. The specimens continued to contract for a period of practically one year, when the maximum contraction was about 0.0006 inch, or 0.06 per cent. After the specimens were more than a year old (460 days and 540 days) they again were kept continually moist and immediately started to expand, but did not regain their former length. The amount of expansion was roughly 0.0004 inch per inch of length, or about 0.0002 inch short of their original length. Note that during the first few days after reimmersion these specimens expanded only from 0.0001 to 0.0002 inch per inch of length and their subsequent expansion was slow, requiring several months to reach the maximum. The above specimens were dried in the rather dry and warm atmosphere of the laboratory, and therefore were almost as dry as it was possible to make them. It will be noticed that there is no great difference in the contraction and expansion of the different mixtures tested, whether they were 1:2:4 or 1:3:6, very wet or very dry. Comparing figure 5 with figure 6, it will be noted that the ultimate contraction is about the same whether or not the concrete was subjected to an initial period of wetting.

Let it be supposed that the ends of a concrete construction are immovable and that it is subjected to extremely dry conditions, so that it will shrink 0.0006 inch per inch of length. Then, if a modulus of elasticity of 3,000,000 pounds per square inch is accepted as correct, the tensile stress produced will be $3{,}000{,}000 \times 0.0006 = 1800$ pounds per square inch. Obviously, under such conditions as these, concrete must crack, since a stress of only 200 pounds per square inch is not far from the maximum tensile strength of concrete. There are, however, very few concrete structures that are subjected to the degree of drying out suffered by the specimens reported, and the results are given merely to show what can and does happen to concrete under conditions favorable to its thorough drying.

These curves show quantitatively what occurs in a concrete pavement just after it is laid and demonstrate the efficacy of the practice of keeping the concrete wet for a short period after pouring. The curves show that concrete remains expanded as long as it is wet and contracts as soon as it begins to dry out, with the consequent tendency to form cracks. In a concrete pavement, where there is always some restraint due to friction at the base, any tendency toward shrinkage will be resisted, and tension will be developed. In the earlier stages of hardening the tensile strength of concrete is very low, and consequently a very minute shrinkage may produce cracking, irrespective of the presence of expansion joints.

A consideration of the excessive shrinkage of concrete due to complete drying out, with a resulting hazard of overstress in tension, shows the great necessity for maintaining concrete structures in a moist condition for a few weeks after pouring. By this practice it is seen that they may be kept expanded, and, therefore, under small compressive stress. When they do dry

out, after several weeks, they shrink and develop tension, but they are then somewhat fortified by their maturity and are better able to resist the tensile stresses developed. The practice of keeping concrete wet must be emphasized from this standpoint, as well as from the fact that by so doing a more complete hydration of the more sluggish particles of cement is effected and the strength increased somewhat thereby. The practice of subjecting the concrete to an initial period of wetting can not wholly prevent cracking, but it does aid in decreasing the number of cracks that form in concrete pavements.

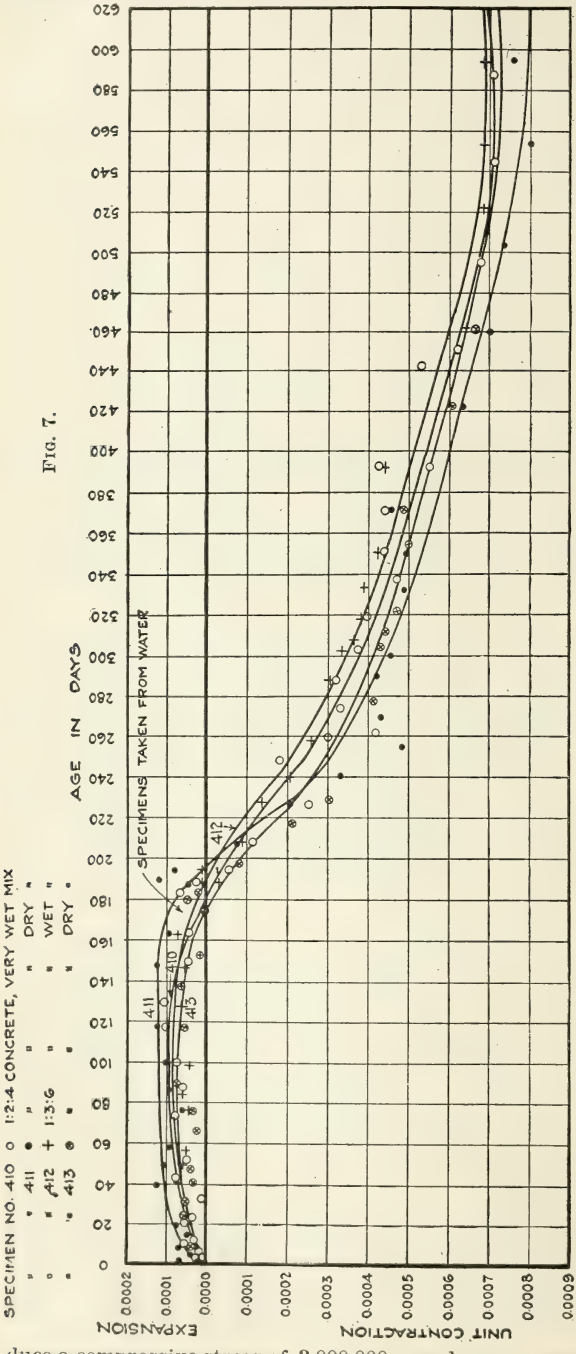

SPECIMEN NO. 410 ○ 1:2:4 CONCRETE, VERY WET MIX
" " 411 ● " " " DRY "
" " 412 + 1:3:6 " " WET "
" " 413 ⊗ " " " DRY "
AGE IN DAYS
SPECIMENS TAKEN FROM WATER
410
411
412
413
EXPANSION
UNIT CONTRACTION

FIG. 7.

1:2:4 AND 1:3:6 CONCRETE; LONG INITIAL WETTING.

On figure 7 are shown four curves giving the expansion and contraction of 1:2:4 and 1:3:6 concrete of very wet and very dry consistencies. These specimens differ from the others in that they were kept in water for a period of about six months, then removed and allowed to dry in the warm, dry air of the laboratory. Note that concrete under constantly moist conditions maintains almost constant expansion while it is moist, and that the amount equals approximately 0.0001 inch, or 0.01 per cent. Theoretically, when the ends of a concrete structure are restrained from movement, this would produce a compressive stress of 3,000,000 pounds per square inch, multiplied by 0.0001 inch, or 300 pounds per square inch, provided stresses can be figured in this

way and are subjected to no other influences. Recent researches[1] have shown that under constant stress concrete exhibits a slow yielding, or "flow," making the deformation produced by constant stress very much greater than that produced by a static stress of short duration. In the curves on figure 7 it is seen, again, that there is very little difference between the contraction and expansion of 1:2:4 and 1:3:6 concrete, whether wet or dry. Apparently there is not enough difference in the degree of richness of the mixture to cause a difference in the contraction and expansion of concrete. The maximum contraction obtained in this set of experiments was about 0.0008 inch per inch of length.

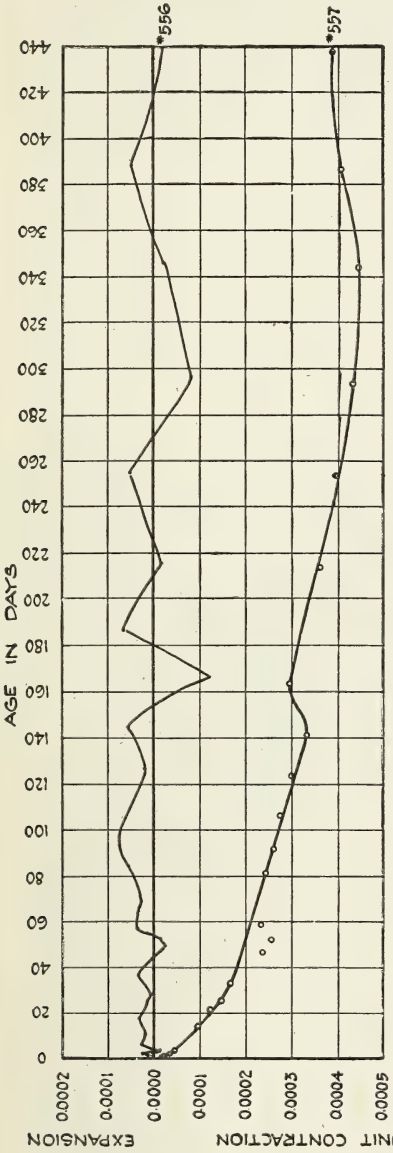


FIG. 8.—Specimen No. 556, 1:2:4 gravel concrete cured outdoors. Specimen No. 557, 1:2:4 gravel concrete 85 per cent cement, 15 per cent hydrated lime.

GRAVEL CONCRETE, STORED OUT OF DOORS.

On figure 8 is shown the effect of exposure to the atmosphere of a specimen made of 1:2:4 gravel concrete. This specimen was stored in a vertical position out of doors at a place where it was in shade for perhaps three or four hours every day. No effort was made to protect it from rain or sun. This curve, like the preceding ones, simply shows the effect of moisture, all temperature effects having been eliminated. It is seen that there has been but very little change in the length of the concrete due to moisture changes in the specimen. This seems reasonable to expect in a specimen cured out of doors, as the alternate wetting and drying to which it was subjected, due to changes in the weather, occurred with such frequency that there was little chance for moisture changes to be effective, and it has been pointed out already that large changes in length, due to moisture changes, are apt to be slow and progressive, although changes of 0.0001 to 0.0002 inch per inch of length may occur in the course of a few days. The influence of moisture on this specimen cured out of doors probably is somewhat typical of the behavior of concrete in roads that have a well-drained subbase.

[1] "Flow of Concrete under Sustained Loads," by E. B. Smith, Proceedings of American Concrete Institute, 1916.

GRAVEL CONCRETE WITH HYDRATED LIME, STORED IN AIR.

Curve 557 on figure 8 shows the contraction of a 1:2:4 gravel concrete specimen in which 15 per cent of hydrated lime was substituted for cement. This specimen was cured indoors and allowed to dry out immediately after molding. Here again, as in the case of the ordinary concrete specimens, we have a progressive contraction, the maximum amount being about 0.00045 inch. This is somewhat less than in the specimen untreated with hydrated lime. As but one specimen was measured, no claim can be made that the hydrated lime aided in decreasing the contraction.

TAR-COATED SPECIMEN.

It is reasonable to expect that any application of more or less waterproof material to the surface of the concrete will greatly retard the absorption of moisture, or, if the concrete be already wet, will prevent it from drying out rapidly. In order to determine the effect of such a coating on the change in length of concrete, a mixture of 1:2:4 concrete, having a crushed gneiss aggregate, was prepared, and measurements were started two days after pouring. It was then immersed in water and the measurements continued. At the end of 13 days the specimen was removed from water and, after surface drying for one day, a hot application of vertical retort tar was made. Note that after 13 days' expansion continued slightly, although the specimen had been removed from the water and coated with tar, while at the end of about 30 days this expansion ceased and a slight contraction began. However, the specimen was still somewhat expanded up to the end of 150 days, after which it contracted very slowly. The tar coating evidently served to retain the moisture in the concrete for a considerable length of time and thus kept it expanded.

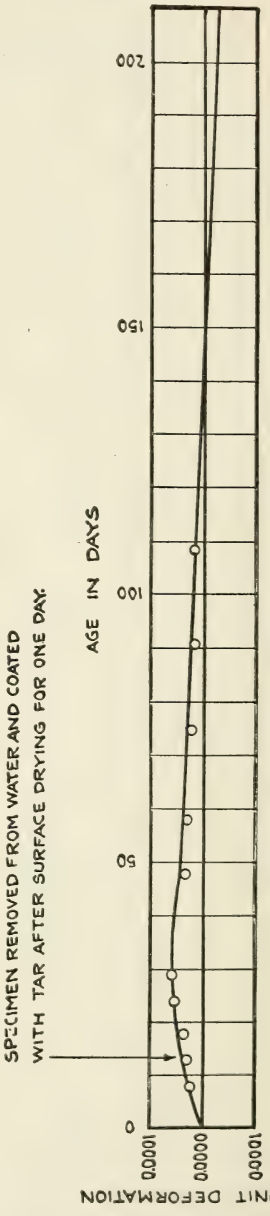


FIG. 9.—Tar coated specimen.

REINFORCED CONCRETE SPECIMENS.

Four specimens were made up of 1:2:4 gravel concrete containing 0.61 per cent, 1.2 per cent, and 1.8 per cent of steel. These specimens were allowed to dry out in the air of the laboratory, and measurements were taken at frequent intervals. The plain gravel specimens showed a maximum contraction of only 0.035 per cent at the age of 6 months, as compared with 0.06 per cent for the crushed gneiss specimens previously reported. This difference in contraction is not due necessarily to the different aggregates. The specimens containing 0.61 and 1.2 per cent steel showed a contraction of only 0.02 per cent,

while the specimen containing 1.8 per cent steel contracted less than 0.01 peh cent, or about one-fourth of the contraction of the plain concrete specimen.

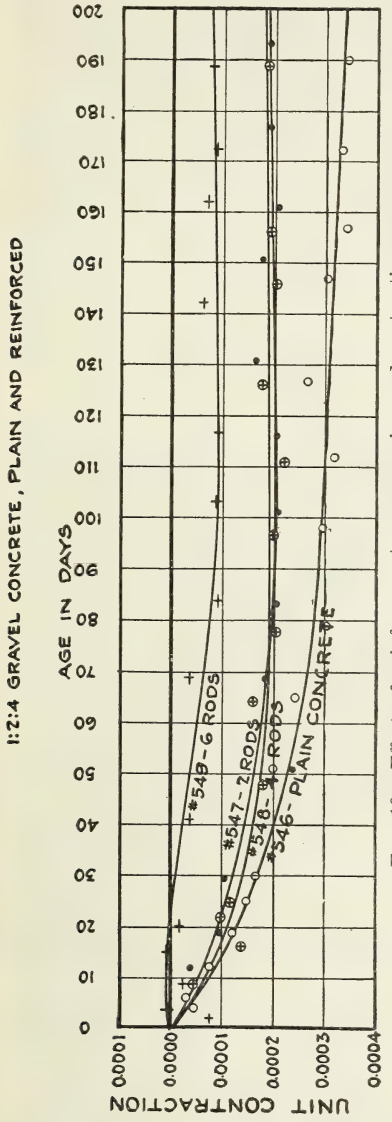


FIG. 10.—Effect of reinforcement on expansion and contraction.

If there were perfect bond between the concrete and the steel, this amount of shrinkage in the concrete would produce a stress of about 3,000 pounds per square inch in compression in the steel reinforcing of specimen No. 549, and about 7,500 pounds per square inch in specimens Nos. 547 and 548. The more concrete is restrained from shrinking, the greater will be the tensile stress induced by the compression in the steel. The specimen containing 1.8 per cent of steel contracted, roughly, 0.0001 inch per inch of length, while the plain, and therefore unrestrained, specimen contracted 0.00035 inch. In other words, the steel prevented the concrete from contracting by an amount equal to 0.00025 inch per inch in length. Assuming the modulus of elasticity of this concrete to be 3,000,000, the tensile stress produced by 0.00025 inch elongation would be 3,000,000 multiplied by 0.00025, equals 750 pounds per square inch, which stress, if it actually existed, would, of course, surely produce cracking of the concrete. If cracks were present in the specimens, they were not discernible, but they usually would be very small, and, moreover, it is probable that the slow flow of concrete previously mentioned took place under the extremely gradually applied load, making the induced tensile stress very much smaller than the calculated amount. Reinforcing, it is seen, does not prevent the contraction of concrete due to the drying out of the moisture, and in view of the fact that steel and concrete have very nearly the same coefficient of expansion and contraction, the steel can not aid in any way in preventing changes due to temperature. Reinforcing can not prevent the cracking of concrete, but it does serve the purpose of holding the cracks together and keeping them exceedingly minute.

SPECIMEN REINFORCED ON ONE SIDE.

If a concrete road be reinforced with steel placed either near the top or bottom surface, any shrinkage resulting from drying out necessarily must be unequal at the two surfaces because of the restraining influences of the steel. To show the relative amounts of this shrinkage a specimen was made of 1:2:4 concrete, reinforced by two ½-inch round rods with their centers placed 1 inch

from the side of the 8 by 8 inch column. The curve on figure 11 was obtained partly by measurement and partly by theory, assuming that the deformations from the reinforced side to the plain side varied as the ordinates to a straight line. This assumption has been shown to be true a number of times in the cases of beams subjected to bending stresses. Note that the steel seems to have had a bending effect on the specimen, the unreinforced side shrinking much more than the reinforced side. The amount of shrinkage on the plain side of the column at the end of one year amounted to approximately 0.1 per cent; that of the steel amounted to 0.03 per cent. Any such shrinkage as this would tend to cause compressive stresses in the concrete on the unreinforced side and tensile stresses in the concrete on the reinforced side. In a concrete pavement, with the reinforcement placed near the top or bottom, there would be unequal shrinkage at these two surfaces, thereby creating a tendency to curl and crack. To eliminate the unequal shrinkage in concrete pavements, due to eccentric

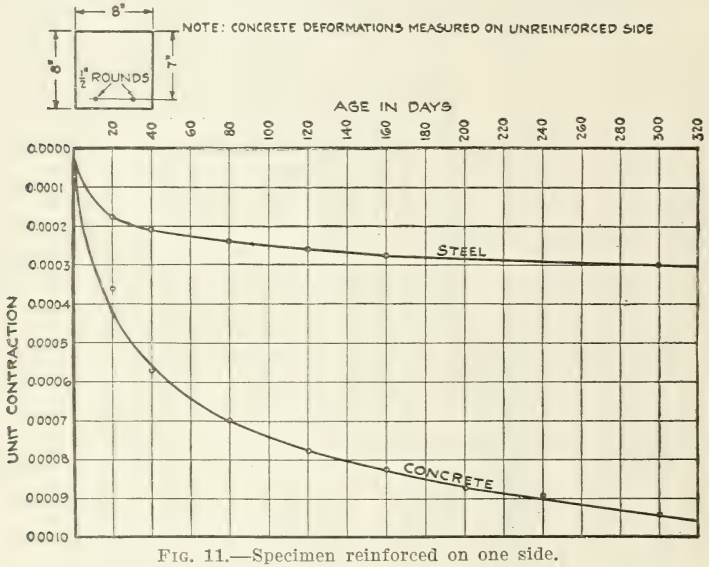


FIG. 11.—Specimen reinforced on one side.

placing of the steel, and at the same time to take care of settlement cracks as efficiently as possible, it is well to place the reinforcement in the center of the pavement.

MEASURING THE EXPANSION AND CONTRACTION OF CONCRETE ROADS.

Although the laboratory measurements of expansion and contraction of concrete gave much information on the influences affecting the length of a concrete road, the actual conditions of moisture in the road are so different from those of the laboratory that it was thought well to obtain additional information of the movements that take place by actually measuring the changes in the road.

A concrete road is subjected to a great range of variables. In the initial stages of its hardening it generally is kept moistened arti-

ficially for a period of 10 days. It is then subjected to all of the changes of temperature and moisture of the atmosphere. In addition to atmospheric influences, however, the condition of the sub-base has an effect on the condition of the concrete. If the sub-base be not well drained, there will be very little tendency for the concrete to dry, irrespective of weather conditions. On the other hand, with a well-drained sub-base the moisture may disappear rapidly after a heavy rain, and the concrete then will dry out quickly. In either case the concrete will absorb much moisture from the underlying soil by capillarity, so that the extreme drying experienced by laboratory specimens rarely will take place in the concrete road. The shrinkage changes of laboratory specimens therefore should be expected rarely in actual construction, as the conditions are not generally favorable. It is possible, however, that expansion due to the absorption of moisture will be accentuated in the concrete road.

A special instrument was designed by one of the authors in order to study the effect of temperature, moisture, and any other physical influences on the expansion and contraction of concrete roads. As the movements in the concrete undoubtedly were small, it was necessary that the measuring apparatus possess great accuracy. It also was necessary, in view of the great temperature ranges to which the instrument would be subjected throughout the day's work and at various seasons of the year, to have some means of correction for these changes in temperature. It was considered advisable, in view of the extremely small changes in length expected in the concrete, to make the measurements over quite a large gauge length, and for this reason 10 feet was selected as the length of the instrument. The device (fig. 12) in its final shape as used on the road, is made up of two gauge tubes, one of steel and one of brass, supported so that they can not bend, and provided with rounded tips against which measurements are made with micrometer screws. By means of these micrometer measurements, corrected to constant temperature, the changes in length between plugs set in the concrete road are obtained.

The tubes A and B are the gauge tubes, and they are supported at frequent intervals by brass disks, D, fastened within a brass casing, E, 2 inches in diameter. This casing extends the full length of the instrument and is surrounded and supported at intervals by another casing, F, 3 inches in diameter. At the ends of this outer casing are two collars, N, which rest in the supporting blocks, G. These blocks are provided with pins, H, whose conical ends fit into holes drilled in bronze plugs set in the road during its construction. One end supporting block, G, is provided with flat-ended contact pins, J, and the block at the other end of the instrument carries micrometer screws, I. Adjusting screws, M, shown in the end view are provided merely to support the instrument on the road, when not in use. The fiber col-

lars, L, likewise are provided merely for protection when the tube is detached from the end supporting block.

The great length of the instrument with the consequent attendant probability of the temperature at the two ends being different, due to one end being in the shade and the other in direct sunlight, led to the use of two gauge tubes of different materials from which to take measurements. Knowing the coefficients of expansion of these tubes, obtained by proper calibration, the difference in the micrometer readings furnished a means of obtaining the temperature of the bars. This temperature then could be used in correcting the micrometer measurements to a standard temperature. Thermometers were inserted in the 2-inch casing at the ends of the instrument. The mean of these end temperature readings, as a rule, approached within 1° C. of the temperature obtained from the micrometer readings.

Before using this instrument on the road it was calibrated in order to obtain the coefficients of expansion of the steel and brass tubes. In doing this a 10-foot steel gauge bar was mounted in a tank of water and immersed about 1 inch below its surface. Thermometers were laid in the water on top of the gauge bar and read from time to time

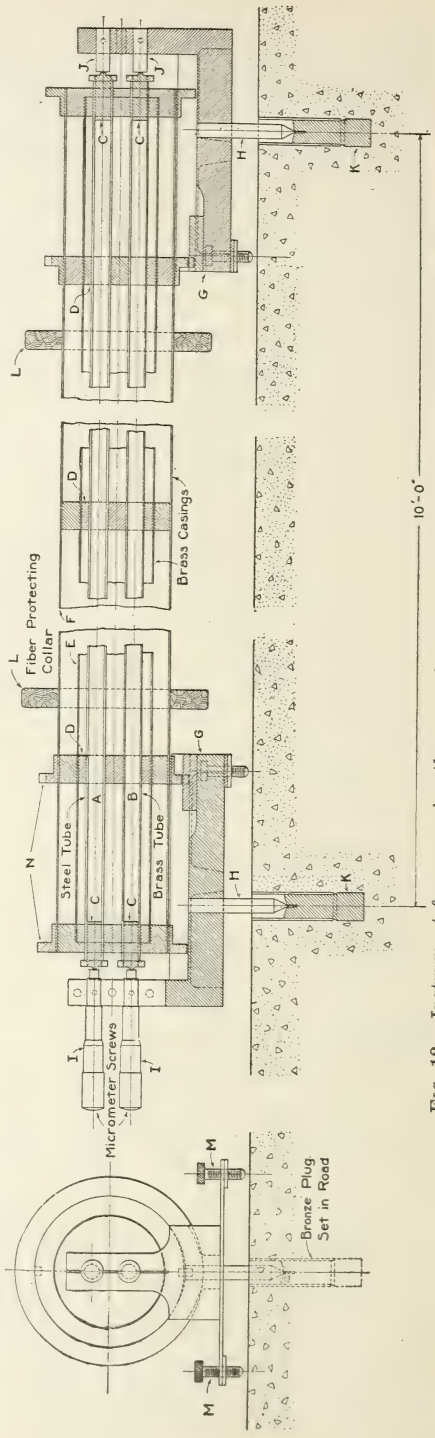


FIG. 12.—Instrument for measuring the expansion and contraction of concrete roads.

to insure that the temperature was not changing. The instrument then was mounted on the gauge bar, and a jet of steam was passed through the inner casing surrounding the steel and brass tubes. When the temperature of this inner casing had become constant, micrometer readings were taken. A stream of cold air then was run through, and again temperature readings were taken at each end of the instrument, until it was determined that the inside temperature had become constant. Micrometer readings were taken again. Several sets of readings made in this way gave values for the coefficient of expansion of the steel tube averaging 0.0000110 per degree centigrade, and for the brass tube 0.0000179. Knowing the difference in readings in the steel and brass tubes at the two measured temperatures, and having determined the coefficients of expansion of the metals, a curve giving the difference in length of the bars at various temperatures was plotted readily. When readings were made out on the road the temperature of the bars of the instrument was obtainable easily by means of the difference in their measured length.

Bronze plugs spaced 10 feet apart were set in the concrete road. A depressed cone formed the top surface, and its center was drilled with a one-sixteenth-inch drill. The top of the plug was protected with a brass tube which was set flush with the surface of the road, and, except when readings were taken, was filled with putty. Great care had to be exercised in setting the plugs as nearly 10 feet apart as possible so as not to exceed the range of the instrument. The greatest possible care likewise was taken to keep the holes in the plugs clean while measurements were being made.

In manipulating the instrument one operator was required at each end. After setting the supporting points of the blocks into the holes drilled in the plugs the brass and steel gauge bars were slid gently through the casing a very short distance, slightly jolting the blocks. This seemed to settle them into place so that check readings could be taken. After each reading the instrument was removed entirely from the holes and reseated. The readings were repeated again, and an average of three or four more was recorded as the true reading for the set. The steel-bar reading then was corrected to what it would have been if the bar had remained at constant temperature, and in this way changes in temperature of the instrument were eliminated.

RESULTS OF TEST MEASUREMENTS AT CHEVY CHASE, MD.

Beginning in September, 1912, a length of experimental road was constructed on Connecticut Avenue, beginning at Bradley Lane and extending north to Chevy Chase Lake. This road was composed of six sections of different varieties, as follows, beginning at Bradley Lane:

Section I. Bituminous concrete, Topeka specification.
Section II. Bituminous concrete, District of Columbia specification.

Section III. Cement concrete, surface treated with bituminous materials.
Section IV. Oil-cement concrete.
Section V. Cement concrete.
Section VI. Vitrified brick.

Some of the above sections were not built in continuous lengths.

Because of unfavorable weather, work was stopped on this road on December 15, after the concrete of Section III had been poured. Work was resumed in the following spring and carried to completion. On the bottom of figure 13 will be found a partial layout of the various sections of the road as constructed, giving the dates of construction and the character of the coarse aggregate. A complete description of the road and method of construction may be found in other publications of this office.[1]

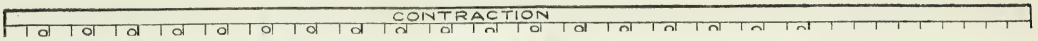
During the construction of the cement concrete sections bronze plugs of the type previously described were inserted in the road surface, spaced 10 feet apart in a line 5 feet from the east side of the road. At every fifth plug there was placed also a transverse plug offset 10 feet from the line of plugs paralleling the road. The layout of the sections of the road measured is shown in figure 13.

The first set of measurements was taken as soon as practicable after the concrete had hardened. The dates and temperatures are given on this plate just above the road layout. Referring to the second set of readings, it will be seen that in general, when the temperature is lower than the initial temperature, the uncracked portions of concrete show contraction, and when the temperature is higher than the initial temperature, expansion occurs. Cracks are indicated by dotted lines and are seen at various intervals throughout the length of the road, in practically all the different sections except that containing limestone aggregate. In the cold weather, during which this set of readings was taken, the cracks opened up, as shown by the expansion readings. The shrinkage of the concrete naturally would cause an opening of the cracks.

In the spring of 1913 a bituminous carpet coat was placed over the concrete up to the end of the oil-cement gravel-aggregate section (station No. 210), and expansion measurements were made in the hot weather of the spring, summer, and fall. It is interesting to note that the readings taken on July 3, 1913, all showed expansion, even those taken over the cracks. Expansion at the cracks as well as in the concrete is rather difficult to account for with certainty. However, during the previous winter the cracks undoubtedly opened up very wide during the coldest weather, owing to low temperature contraction, aided perhaps by the freezing of water in the cracks, and became filled with material from the road which prevented

[1] Office of Public Roads Circular No. 99. U. S. Department of Agriculture Bulletin No. 105.

EXPANSION AND CONTRACTION — INCHES IN 10 FEET



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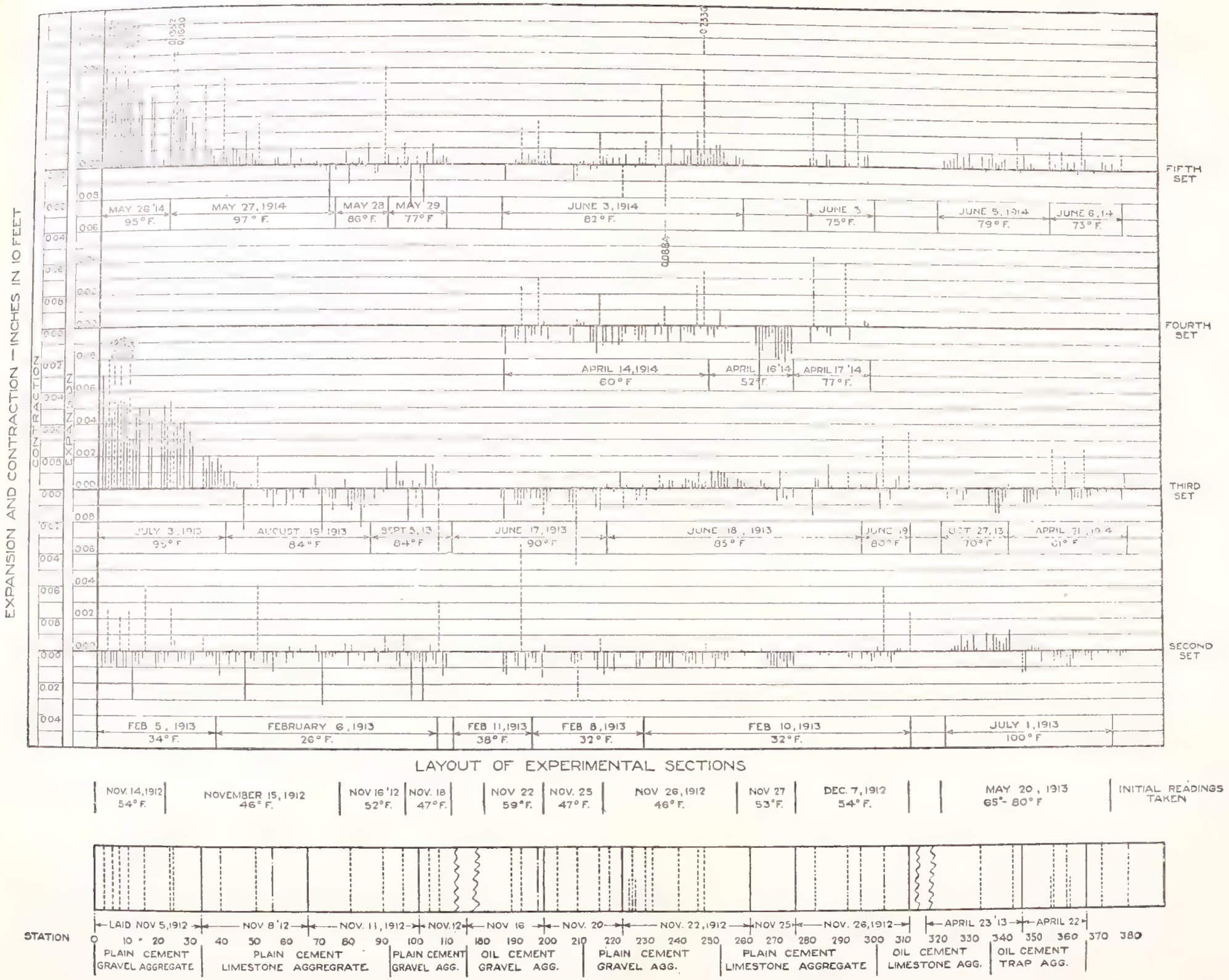
EXPANSION AND CONTRACTION — INCHES IN 10 FEET
CONTRACTION
EXPANSION
FIFTH SET
FOURTH SET
THIRD SET
SECOND SET
MAY 26 '14 95° F.
MAY 27, 1914 97° F.
MAY 28 86° F.
MAY 29 77° F.
JUNE 3, 1914 82° F.
JUNE 5 75° F.
JUNE 5, 1914 79° F.
JUNE 6, 14 73° F.
APRIL 14, 1914 60° F
APRIL 16 '14 52° F.
APRIL 17 '14 77° F.
JULY 3, 1913 95° F
AUGUST 19, 1913 84° F
SEPT 5, 13 84° F
JUNE 17, 1913 90° F
JUNE 18, 1913 85° F
JUNE 19 80° F
OCT 27, 13 70° F
APRIL 21, 19 4 61° F
FEB 5, 1913 34° F.
FEBRUARY 6, 1913 26° F.
FEB 11, 1913 38° F.
FEB 8, 1913 32° F.
FEB 10, 1913 32° F.
JULY 1, 1913 100° F
LAYOUT OF EXPERIMENTAL SECTIONS
NOV. 14, 1912 54° F.
NOVEMBER 15, 1912 46° F.
NOV 16 '12 52° F.
NOV. 18 47° F.
NOV 22 59° F.
NOV. 25 47° F.
NOV 26, 1912 46° F.
NOV 27 53° F.
DEC. 7, 1912 54° F.
MAY 20, 1913 65°- 80° F
INITIAL READINGS TAKEN
STATION
LAID NOV 5, 1912
NOV 8 '12
NOV. 11, 1912
NOV. 12
NOV 16
NOV. 20
NOV. 22, 1912
NOV 25
NOV. 26, 1912
APRIL 23 '13
APRIL 22
0 10 20 30 40 50 60 70 80 90 100 110 180 190 200 210 220 230 240 250 260 270 280 290 300 310 320 330 340 350 360 370 380
PLAIN CEMENT GRAVEL AGGREGATE
PLAIN CEMENT LIMESTONE AGGREGRATE
PLAIN CEMENT GRAVEL AGG.
OIL CEMENT GRAVEL AGG.
PLAIN CEMENT GRAVEL AGG.
PLAIN CEMENT LIMESTONE AGGREGATE
OIL CEMENT LIMESTONE AGG.
OIL CEMENT TRAP AGG.

FIG. 13.—Expansion and contraction of concrete road, Connecticut Ave. extended, Chevy Chase, Md. Laid in 1912 and 1913.

them from closing when the expansion of the adjacent concrete took place. The section of road read on July 3 was adjacent to a stretch of bituminous concrete laid on a concrete base. On the very hot day preceding these readings there was an upheaval at the junction of the concrete section with the bituminous concrete section, and the concrete base of the bituminous pavement was sheared off to some extent. Note that one of the cracks had opened more than one-eighth of an inch when the readings were taken.

Measurements made on August 19 are very little different from those of the preceding February, notwithstanding the high temperature existing during the August readings. The September 5 and June 17 readings also are peculiar in that they show very little change from those of the preceding winter, and, moreover, the June 17 readings still show contraction, notwithstanding the hot weather. On June 18, with the temperature not greatly different from that of the preceding day, a slight expansion was shown. No definite conclusions can be drawn from the remaining readings of the third set. Some of the cracks which had opened in the preceding winter remained open during the summer, and others became smaller.

In April, 1914, an incomplete set of readings was taken and the concrete in general showed decided contraction compared with the preceding summer. The contraction of the concrete was accompanied by an opening of the cracks. The low temperature here seems to have played an important part in influencing the length of the concrete.

The fifth set of readings, taken in the spring and summer of 1914, on the whole shows the same characteristics as the third set. In the previous July (1913) the section of road which had buckled was cut out and filled with three double courses of vitrified paving brick with tarred joints. In the spring of 1914 buckling again took place at the same spot, and the bricks were removed and the space filled with concrete.

Note that at the fifth set of readings some of the cracks showed by actual measurement an opening of nearly one-quarter of an inch at the section where maximum expansion took place. The crack openings were even wider than during the preceding summer. Unfortunately, no measurements were made over this section during the winter of 1914. It is probable, however, that such readings would have shown that the cracks had opened very wide at this season and then were prevented from closing again because of becoming filled with loose material. It will be seen that at other sections of the road cracks which were indicated as quite small by some of the previous readings had opened wide. Note the large expansion in the crack which opened in the plain-cement gravel-aggregate section, read on

June 3, 1914, and the comparatively large contraction in the crack about 100 feet away.

Figure 15 plots the results of that part of the Chevy Chase measurements taken over the uncracked portion of the concrete. The ordinates represent the unit deformations of the solid concrete and do not include the movement at the cracks, and the abscissas represent age. At the bottom are plotted temperature and precipitation measurements for the vicinity of Washington, supplied by the Weather Bureau. The daily precipitation records were averaged for each month, and the average precipitation for the month is plotted on an exaggerated scale and is shown by the dotted line. It will be seen that there is no decided relation between the shape of the expansion and contraction curves and that of the precipitation curve. On

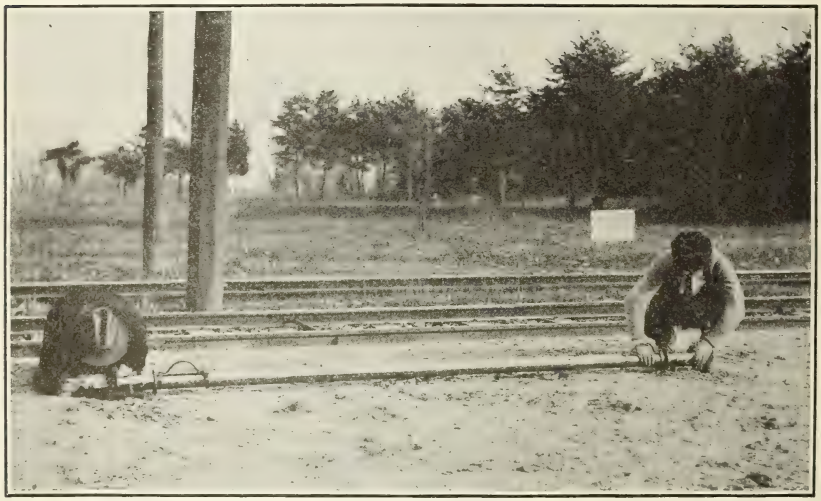

FIG. 14.—The measuring instrument in use on the Chevy Chase Road.

the other hand, there is a tendency for the expansion and contraction curves to conform with the temperature curve. Note that as the temperature decreases at the approach of winter the concrete contracts, and in the summer season, during the highest temperatures, the concrete expands. It would seem from this set of measurements that temperature changes have played a more important part than have atmospheric moisture changes in influencing the movements of the concrete. The moisture in the concrete may or may not bear any relation to the atmospheric moisture, but will be influenced by the degree of wetness of the sub-base. Therefore, no very great importance can be attached to the precipitation record. Note that at the beginning of the measurements, just after the concrete was laid, there was a contraction in every case, notwithstanding the fact that the temperature remained not far from constant. It would seem that this

initial contraction must be explained by the drying out of the moisture in the concrete. It has been shown in the previously described

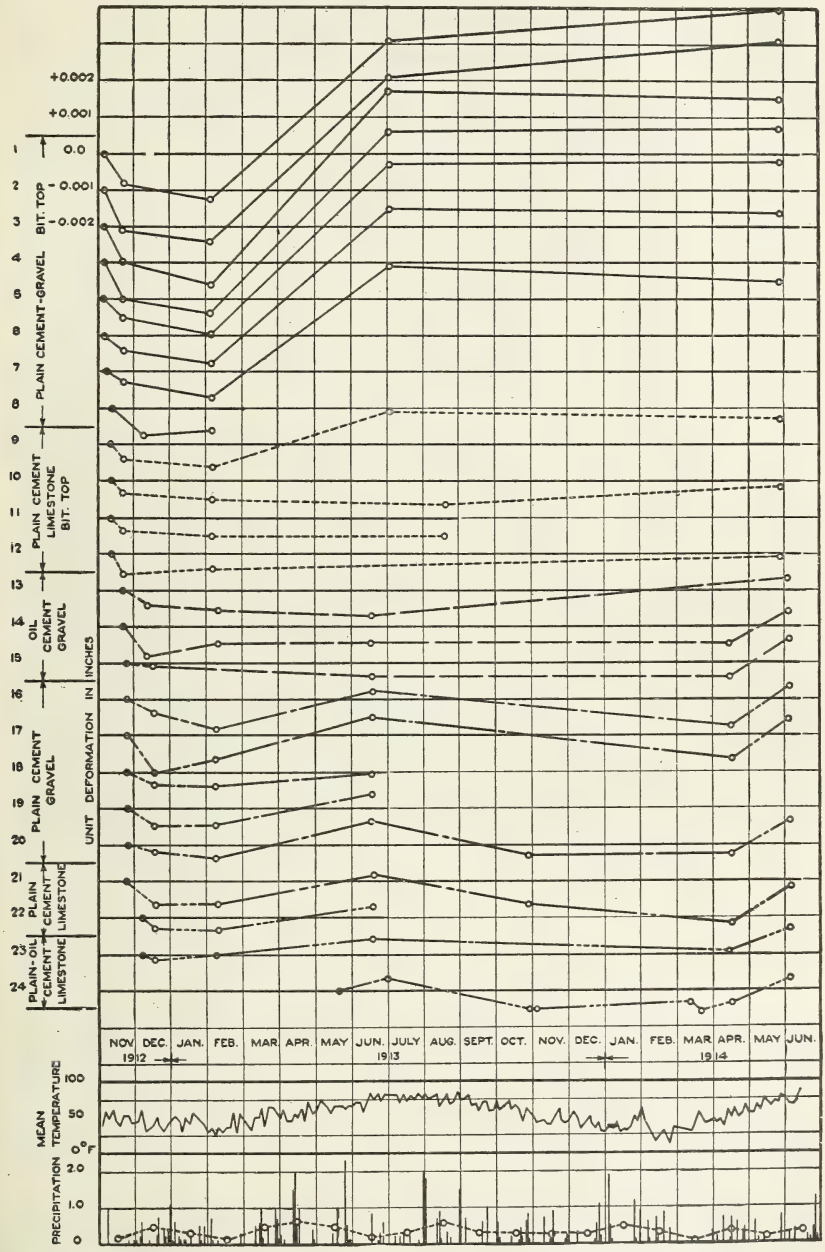

FIG. 15.—Curves of unit expansion and contraction of uncracked portions of concrete road, Chevy Chase, Md.

laboratory tests that great shrinkage of concrete can take place during the initial stages of hardening, due to the drying out of the moisture,

and it is an observable fact that as soon as the wet-earth covering is removed from the surface of the concrete it begins to dry out and, necessarily, to shrink. The maximum average shrinkage shown by the concrete in any of the sections of different mixtures was approximately 0.0001 inch per inch of length, and this occurred about three months after the pavement was laid. The temperature in this time, however, had dropped 20°, and this fall in temperature accounts almost exactly for the shrinkage. It has been shown by means of laboratory specimens stored out of doors and subjected to all the changes of the atmosphere that very little change in length takes place under such conditions. It seems probable that the moisture content of the concrete at Chevy Chase changed so little that the length of the concrete was very little affected thereby. A hard rain, thoroughly soaking the concrete, will have no immediate great effect upon its length. It has been pointed out that moisture changes are rather slow and progressive, and therefore it is unlikely that hard rains of even several days' duration will have great effect on the expansion of the concrete in the road.

EXPANSION AND CONTRACTION OF OHIO POST ROAD.[1]

These measurements were taken over three 300-foot experimental sections of the concrete Ohio Post Road constructed in 1914 under the supervision of the Office of Public Roads. The Ohio Post Road is located partly in Muskingum County and partly in Licking County, Ohio, and runs west from Zanesville, Ohio, for 24 miles over the old National Pike to the Moscow Bridge over the South Fork of the Licking River. This road was constructed on a sub-base composed mainly of a stiff red clay. The total width of concrete surfacing is 16 feet, with a thickness of 6 inches at the edges and 8 inches at the center. Expansion joints made of one thickness of 2-ply tar paper were spaced 30 feet apart throughout the length of the road, with the exception of the three experimental sections, on each of which the spacing varied from 20 feet to 100 feet, intervening sections being 40, 60, and 80 feet long. Expansion joints were placed at an angle of 15° across the road. Both gravel and crushed stone were used as coarse aggregate, the proportions in the former case being 1:1½:3 and in the latter 1:1¾:3. Crushed stone used in the experimental sections was obtained from limestone quarried on the Scioto River at Marble Cliff. The sand and gravel were obtained from a washing plant at Dresden, Ohio.

As soon after laying as possible the concrete surface was covered with canvas, which was removed when the concrete was 24 hours old and replaced by a 2-inch earth covering. This was allowed to remain

[1] The authors desire to acknowledge the assistance of the Ohio State Highway Department in conducting the tests on this road.

on the road for two weeks and was kept wet. At the end of that time it was removed and the road opened.

LOCATION OF EXPERIMENTAL SECTIONS.

The three 300-foot experimental sections referred to above were located on the road as follows:

Section I, in Licking County, one-half mile east of National Road Station. This section comprised the last 300 feet at the bottom of a 4 per cent grade 2,000 feet long. The coarse aggregate was limestone, and the section was laid July 6, 1914. The distances between expansion joints varied from 100 to 20 feet, as noted above, with the 100-foot section at the bottom of the grade. At the time of laying bronze plugs, similar to those used in the Chevy Chase experiments, were cast 10 feet apart along the center of the road. Readings on this section were taken on July 7, 8, and 22, on October 31, 1914, on March 4 and June 19, 1915, and on February 25, 1916.

Section II, in Licking County, about 500 feet east of Moscow Bridge, on a 0.4 per cent grade. Limestone was used as the coarse aggregate, and the spacing of the joints and placing of the measuring plugs was the same as on Section I. The first 180 feet of this section was laid on July 29 and the last 120 feet on July 30. This break was caused by an accident to the mixer. Readings were taken on August 1, November 2, 1914, on March 3 and June 17, 1915, and on February 25, 1916.

Section III, in Muskingum County, at Mount Sterling. This section was laid at the bottom of a vertical curve with a 6 per cent grade 400 feet long rising eastward and a 6 per cent grade 600 feet long rising westward. Gravel was used as a coarse aggregate. The section was laid on November 5, 1914, and readings were taken November 6 and 7, 1914, March 6 and June 15, 1915, and February 22, 1916.

Measurements on Section I.

The initial readings on Section I were taken on July 7, 1914, one day after the concrete was laid. The temperature of the concrete was determined by means of a thermometer inserted in a small brass tube cast in the top of the pavement, the thermometer bulb being about 4 inches below the surface of the pavement. The hole was packed with putty and covered with a box to protect it from the sun, and here the thermometer was allowed to remain until a uniform temperature was obtained. On July 8, one day after making the initial readings, or two days after the concrete was laid, the second set of readings was taken and is shown graphically on the curve. If a crack is included within the 10-foot gage length, the reading is indicated by a dotted line; if a construction joint is included it is shown by a dash and dot line. Almost all the readings taken over

the solid concrete show a slight contraction, while the joints show an expansion, or, in other words, they have opened slightly. The contraction of the concrete took place notwithstanding the fact that it was wet continually. It is to be noted, however, that the temperature fell from 82° on July 7 to 75° on July 8, and this probably accounts for the slight contraction observed.

Up to July 22 the road was kept covered with wet clay, and the third set of readings was taken on this date. Here it is noticed that there is a slight expansion of the concrete with a large contraction at three of the joints and an expansion at two. The temperature at these readings was slightly higher than that taken during the initial readings. This, combined with the moisture expansion, could account

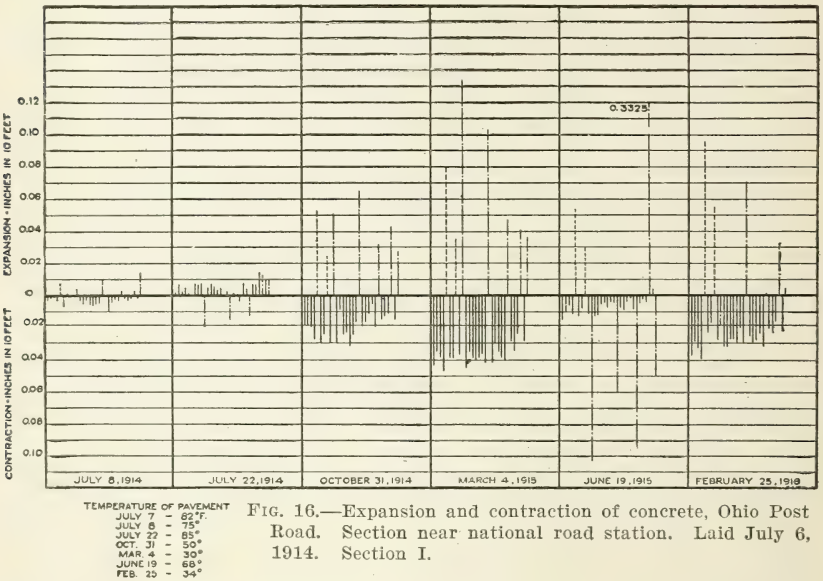

FIG. 16.—Expansion and contraction of concrete, Ohio Post Road. Section near national road station. Laid July 6, 1914. Section I.

for the slight expansion noted in the concrete. But during this period of initial hardening, while the concrete was kept wet, it is seen that very little change took place in its length. It is important to note, however, that even on the second day, when the readings showed a slight contraction of the concrete, a transverse crack appeared. The slight tensile stress induced in the weak green concrete by the contraction evidently was enough to produce rupture.

Just after July 22 the earth covering was removed from the road surface, and it was subjected directly to atmospheric influences. On October 31, with the pavement temperature at 50° (32° lower than the initial temperature), the uncracked concrete showed large contraction, while the cracks and joints opened or gave an expansion

reading on the instrument. The total contraction over the uncracked portions of the pavement equaled 0.462 inch in a total length of 230 feet, or 0.00017 inch per inch of length. The calculated contraction for the fall in temperature between the initial reading (82°) and this reading (50°) equals 0.000176 inch per inch of length, almost identical with the actual measured contraction.

On March 4, when the temperature of the pavement was 30° F., another set of readings was taken. In the interval the pavement had been subjected to the extreme cold of the winter. Here again is seen the effect of change in temperature upon the concrete. That part of it which remained free from cracks contracted 0.000307 inch per inch of length. The decrease in temperature during this period was 52°, and hence the theoretical contraction would be equal to 0.00029 inch per inch of length, so that here again the temperature influence seems to be borne out by actual measurement. It will be seen that the cracks and expansion joints in this section opened considerably, and the colder the weather the greater the openings became.

In June, 1915, not quite a year after the road was constructed, another set of readings was made and gave the results shown on the curve. The warm weather had decreased the contraction of the concrete below the amount shown in the preceding March. This section was laid in warm weather when the temperature exceeded 82° and the temperature for the pavement on June 19 was only 68°, so that some contraction of the uncracked concrete should be expected. This amounted to 0.0167 inch, or 0.00006 inch per inch of length. The theoretical contraction for this fall in temperature is 0.000077 inch, just a little more than the actual measured contraction. A feature of this measurement is the great contraction at some of the expansion joints and a very large expansion at another joint and at two of the cracks. The large contraction or closing of some of the joints and the large opening at one may be accounted for by the relative movements of the slabs due to inequalities in the sub-base and to the fact that the section under test is at the bottom of a long 4 per cent grade.

In February, 1916, the last set of measurements was taken in cold weather. Here again the contracting effect of low temperatures is seen on that part of the concrete which has remained intact. A contraction of 0.00023 inch per inch of length occurred by actual measurement, whereas the figured temperature contraction was 0.000264 inch per inch of length. Temperature again has played a prominent part in influencing the length of the concrete. Note that the 100-foot length cracked in two places, whereas the sections of smaller length did not crack.

Measurements on Section II.

Ohio Post Road at Moscow Bridge.

Section II was laid on a 0.4 per cent grade with limestone aggregate with joints spaced successively 20, 40, 60, 80, and 100 feet apart. This section, laid one month later than Section I, showed much the same characteristics as far as expansion and contraction are concerned. As the weather became colder and colder, the concrete showed more and more contraction. In the hot weather of the summer one year after laying the concrete showed about the same amount of expansion that it showed three days after laying. One of the cracks, however, that had opened in the preceding winter, instead of closing because of the expansion of the concrete, remained open, probably

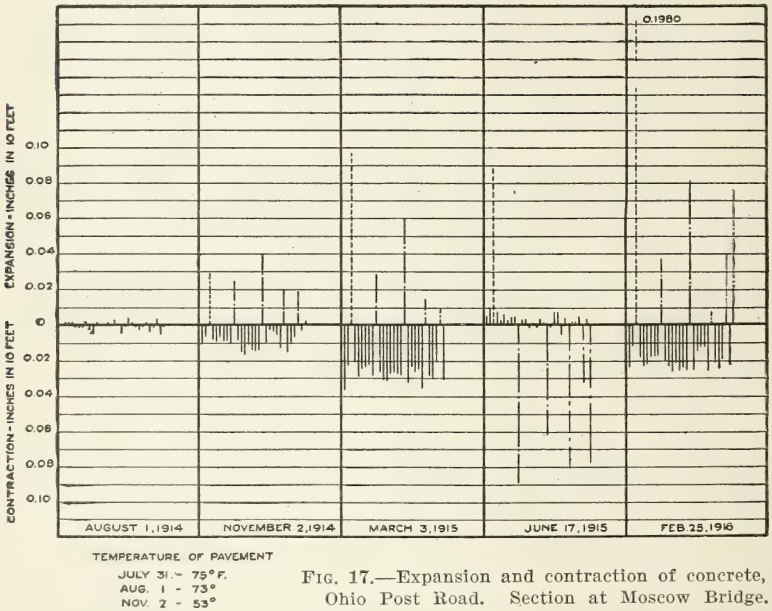

Fig. 17.—Expansion and contraction of concrete, Ohio Post Road. Section at Moscow Bridge. Laid July 29–30, 1914. Section II.

owing to the presence of foreign material. This same crack opened considerably wider in the cold weather of the following winter, as seen in the measurements of February 25, and the remaining joints likewise expanded considerably. Note that a crack formed in the 100-foot section and did not form in the 20, 40, 60, or 80-foot sections.

Measurements on Section III.

Ohio Post Road at Mount Sterling.

Section III shows much the same characteristics as the preceding Sections I and II. This section was laid on November 5, and the initial readings were taken on November 6 at a temperature of 51° F.

On November 7 the second set of readings was taken at a temperature of 54° F. A very small expansion of the concrete was indicated, but at one of the joints a small expansion took place. This is somewhat hard to explain but is of no practical consequence, since it is so small. On March 6 the third set of measurements was taken when the temperature was 37° F., or 14° lower than the initial temperature. Note the large contraction of the concrete and the correspondingly large expansion at the joints and at the single crack that formed in the 100-foot section.

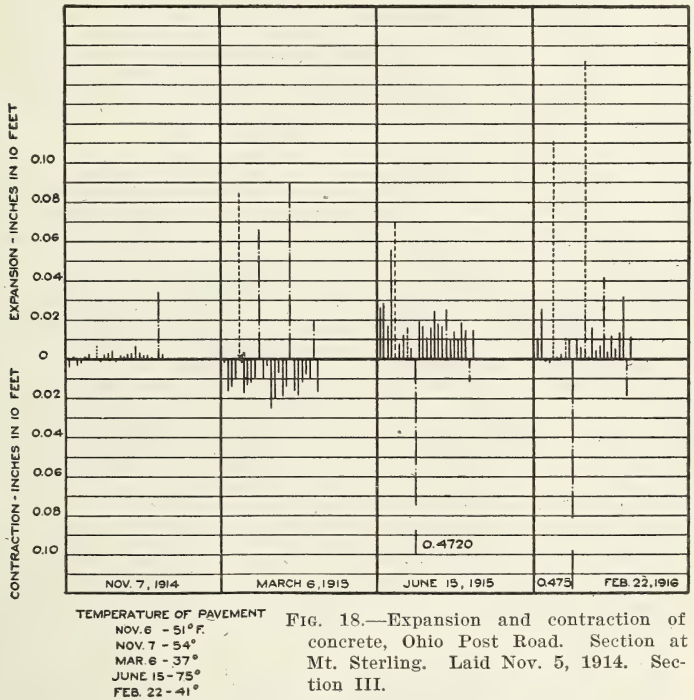

FIG. 18.—Expansion and contraction of concrete, Ohio Post Road. Section at Mt. Sterling. Laid Nov. 5, 1914. Section III.

On June 15 the fourth set of readings was taken at a temperature of 75° or 24° warmer than when the initial readings were made. Again it will be noticed that the uncracked portions of the concrete have expanded with the higher temperature. A second crack had formed during the previous winter, and it, together with the first formed crack, showed expansion or widening. Note the enormous contraction of one of the expansion joints, a contraction of 0.472 or almost one-half inch. One side of this joint overrode the other, so that it projected above the surface of the road about $1\frac{1}{2}$ inches. The last set of readings was taken on February 22, when the temperature was 10° F. below the initial temperature of the road. Enormous expansions are seen to have occurred at the cracks and smaller expan-

sions at some of the expansion joints, and the joint which had pushed together and overrode during the preceding summer remained in the same condition.

In an effort to determine whether atmospheric moisture or temperature played the most important part in influencing the expansion

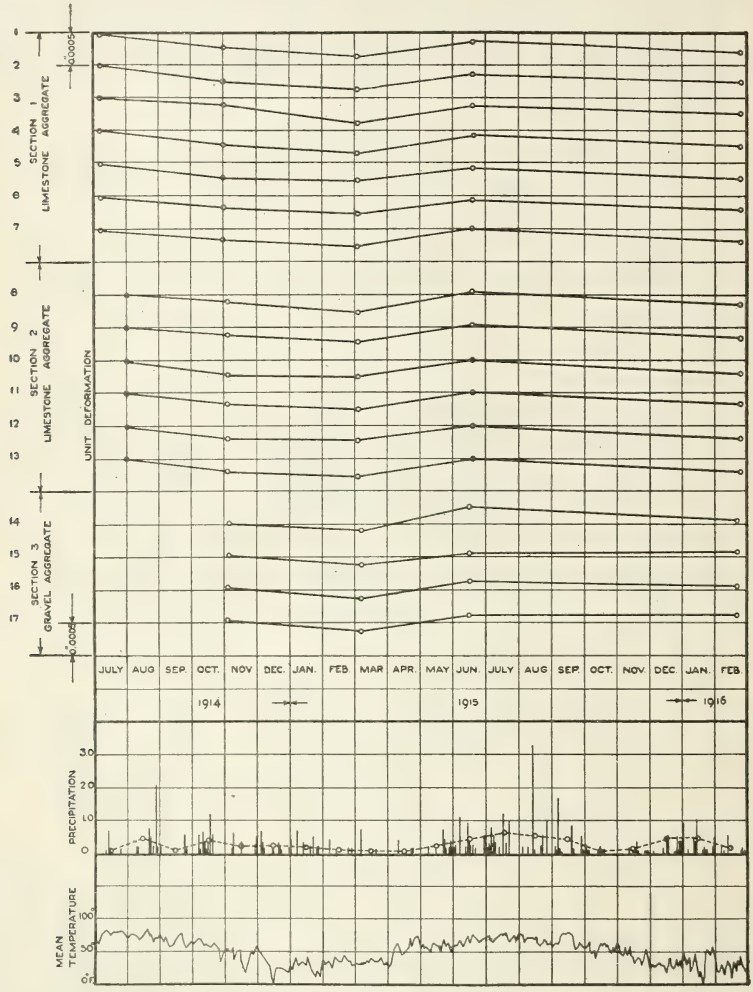

FIG 19.—Curves of unit of expansion and contraction of uncracked portions of concrete road, Ohio Post Road.

and contraction of the Ohio road, the curves shown in figure 19 were plotted. The unit expansions and contractions shown were obtained by summing up the changes in the concrete in the uncracked portions. Each curve represents the unit deformation in a different slab of concrete included between different joints or cracks. In the same section of road these curves should be of practically the same

shape, since the kind of concrete and temperature and other conditions were identical. The precipitation records were obtained from the Weather Bureau records for Columbus, Ohio, and are approximately correct for the three different sections of road measured. The precipitation records during each month were averaged, and the dotted curve represents this average. It is difficult to distinguish the effect of temperature from that of moisture, as indicated by the precipitation curve, since they are so nearly identical. Again, it must be pointed out that the condition of moisture in the concrete is dependent on the moisture in the sub-base rather than on atmosphere moisture, and the precipitation curve is only a general indication of the moisture in the sub-base.

GENERAL DISCUSSION OF THE EXPANSION AND CONTRACTION OF CONCRETE PAVEMENTS.

The preceding laboratory and field measurements show that concrete changes in length owing to at least two separate agencies: (1) Change in moisture content and (2) change in temperature.

(1) *Change in moisture content.*—By laboratory measurements made on large specimens it has been demonstrated that concrete changes in length from its wet condition just after setting to an extremely dry condition at six months or one year later by an amount equal to 0.0005 to 0.0006 inch per inch of length. A change of 0.0006 inch is as much as would be caused by a change in temperature of $0.06 \div 0.0000055 = 109°$ F. and would produce considerable stress under favorable conditions. This change, however, is a very slow one. It occurs most rapidly during the first few weeks of drying out and becomes very slow at the end of three months. At one year the change due to drying will have become constant in amount. It has also been seen that when concrete is kept wet it does not contract, but it expands and maintains a constant expansion of about 0.0001 inch per inch of length. Furthermore, it has been demonstrated that by subjecting hardened concrete to alternate wetting and drying, its length may be changed irrespective of temperature changes. Such moisture changes, however, are rather slow in their action and a prolonged period of wet conditions or a prolonged period of dryness is necessary to effect a large change in the length of the concrete such as might be obtained in a very short time by the influence of temperature. When specimens are stored in the weather and subjected to rain and sunshine, they change very little in length because of moisture changes, unlike specimens that are stored under prolonged conditions of extreme wetness or dryness.

In the field measurements on the Chevy Chase and Ohio Post roads, except that at Mount Sterling, Section III, it is difficult to distinguish the effects of moisture, since apparently they are overshadowed so

greatly by the temperature expansion and contraction. It seems that the concrete in the road, when subjected to actual weather conditions, does not suffer the prolonged extreme ranges of moisture content suffered by the laboratory concrete specimens kept indoors in the dry air of the laboratory and therefore does not expand or contract because of moisture changes to the extent that the laboratory specimens change. Undoubtedly in warm, dry weather there will be some slight contraction just after the moisture is allowed to dry out from the concrete, particularly in a well-drained sub-base. It seems that enough of the water absorbed by the concrete, due to rains or to capillarity, remains in the concrete during the dry weather to prevent much change in length. There may be conditions of prolonged extremes of wetness and dryness in the road which will affect the expansion and contraction to an appreciable extent. Thus in the spring of the year the prolonged moisture of the previous winter might so aid the expansion occurring during the first day of high temperature that the road will heave where proper allowance has not been made for this expansion. There are also conditions of poor drainage in the sub-base, particularly in a low section in the road, where the concrete will be practically constantly saturated, in which case the expanding effect of the moisture will be in evidence.

(2) *Effect of variations in temperature—field measurements.*—It has been pointed out that, as a rule, the concrete in a road expands and contracts as the temperature rises and falls. It will be interesting to compare the actual measurements of the expansion and contraction of the concrete in the road with the calculated change, assuming no friction at the base and assuming a coefficient of expansion of 0.0000055 per degree F. Table I shows a comparison of the actual with the theoretical unit changes in the concrete of the Ohio Post Road.

TABLE I.—*Change in length of concrete in Ohio Post Road.*

	Section I.				Section II.	
	Oct. 31.	Mar. 4.	June 19.	Feb. 25.	Nov. 2.	Mar. 3.
Change in temperature	−32	−52	−14	−48	−22	−45
Actual unit change	−0.00017	−0.00031	−0.000064	−0.00023	−0.000076	−0.000227
Calculated temperature change	−0.000176	−0.00029	−0.000077	−0.00026	−0.000121	−0.000248

	Section II.		Section III.			
	June 17.	Feb. 25.	Nov. 7.	Mar. 6.	June 15.	Feb. 22.
Change in temperature	+3	−38	+3	−14	+24	−10
Actual unit change	+0.000024	−0.000168	+0.0000096	−0.000109	+0.000148	+0.000072
Calculated temperature change	+0.000017	−0.00021	+0.0000165	−0.000077	+0.000132	−0.000055

These comparisons of the actual change with the theoretical change, considering temperature alone to be the cause, are interesting. Observe that in Section I the agreement of the theoretical with the actual change in length is quite close, indicating that temperature was almost the sole cause of the change, and indicating, moreover, that the resisting effect of friction at the base must have been small. In Section II the agreement is not quite so close, and in Section III the agreement is poor. The actual unit change in many cases is in excess of the calculated temperature change, thus indicating that moisture is causing some expansion and also that the restraining effect of friction in preventing expansion and contraction may be quite small.

The discrepancies between the measured changes and theoretical changes are very noticeable in Section III. It will be seen from the description of Section III that it lies at the bottom of two 6 per cent grades and the conditions are very favorable for a wet sub-base. Moreover, this section of the road was covered continually with mud tracked in from adjacent roads, and this aided in preserving the road in a moist condition. The actual change in length on June 15 and February 22 was greater than the calculated change, and these days were preceded by a considerable period of wet weather, as shown by the precipitation curve. These conditions were promotive of a wet sub-base, and this probably accounts for the increase in expansion of the actual over the theoretical. On June 15 the actual expansion is 0.000148 minus 0.000132, or 0.000016. On February 22 the excess unit expansion equals 0.000127 inch. As shown by laboratory measurements, this is approximately the amount of expansion produced in concrete by continued moisture, and this measurement therefore tends to confirm the presumption that the moisture effect is causing the difference between the actual expansion and calculated temperature expansion. The apparently small effect of friction in preventing expansion is interesting and is not unreasonable when it is considered that the pavement is subjected to continued vibration which would tend to relieve temporarily any friction between a wet clay sub-base and the concrete. Moreover, the slow yielding of the sub-base as the concrete creeps helps to relieve the stresses of friction.

The foregoing expansion and contraction measurements are presented in the hope that they will be of assistance to the engineer having charge of concrete road construction. Much theory might be developed from these measurements, but this development, together with the practical application of the results, will be left for the present to the constructing engineer. Some broad conclusions may be stated as the result of the investigations described, combined with the investigations of others.

CONCLUSIONS, BASED ON EXPANSION AND CONTRACTION MEASUREMENTS.

1. Neat cement when allowed to dry, first contracts rapidly, then more slowly. The amount of contraction seems to vary with the cement, size of specimen, and condition of atmosphere in which drying takes place. The amount at 28 days is about 0.1 per cent and at 6 months about 0.2 per cent.

2. Mortar contracts on hardening in air and expands on hardening in water. The contraction in warm, dry air at 28 days is about 0.045 per cent for 1:2 and 1:3 mortar and at 6 months is 0.078 for 1:3 mortar and 0.085 for 1:2 mortar. The expansion in water is 0.01 per cent for 1:3 and 0.017 for 1:2 mortar at 28 days, and at 6 months 0.013 for 1:3 and 0.02 per cent for 1:2 mortar.

3. Both 1:2:4 and 1:3:6 concrete contract on drying in warm, dry air from 0.02 to 0.04 per cent at 28 days and from 0.04 to 0.07 per cent at 6 months. When hardening in water an expansion of about 0.01 per cent takes place at 28 days and 6 months in 1:2:4 and 1:3:6 concrete.

4. The richness of the mix of concrete seems to exert a small influence on the contraction; the richer the mix the greater the change in length.

5. Concrete alternately wetted and dried may be made to expand and contract owing to these causes. The expansion due to wetting is more rapid than the contraction on drying. The thoroughly dried specimens of concrete do not recover their original wet length when immersed.

6. Concrete stored in the outer air and exposed to the weather does not contract to the same extent as the above described specimens except under very dry conditions.

7. A waterproof covering, such as coal tar, prevents the rapid change in moisture content and greatly retards the expansion and contraction.

8. Reinforcement decreases, but does not prevent, the shrinkage and expansion of concrete due to drying and has no effect on temperature changes. Reinforcement can not, therefore, entirely prevent cracks, but seems to distribute them and keep them small.

9. Concrete roads are affected by both temperature and moisture. When the drainage is good and the sub-base not wet, the temperature effects seem to be most important. A wet sub-base may add to the temperature expansion by about 0.01 to 0.02 per cent. The restraining effect of friction at the base seems to be almost negligible when figuring temperature and moisture expansion and contraction. In very dry climates shrinkage due to drying must be added to contrac-

tion due to fall in temperature. A shrinkage of 0.04 per cent (one-quarter inch in 50 feet) is a safe allowance due to drying.

10. Temperature at time of construction of road should be considered in designing joints. Cold-weather construction requires a full allowance for temperature expansion and, on wet sub-bases, for moisture expansion also. Hot-weather construction theoretically requires no joints at all, even in wet sub-bases, as the temperature contraction exceeds the moisture expansion. However, the difficulty of keeping the cracks clear probably renders joints imperative.

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